Renewable and Sustainable Energy Reviews 16 (2012) 5245–5259

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Estimation of the energetic and environmental impacts of a roof-mounted building-integrated photovoltaic systems

Federica Cucchiella*, Idiano D'Adamo

Department of Electric and Information Engineering, Faculty of Engineering, University of L'Aquila, Via G. Gronchi 18, Zona Industriale Pile, 67100 L'Aquila, Italy

A R T I C L E I N F O

Article history:
Received 9 January 2012
Received in revised form
19 April 2012
Accepted 20 April 2012
Available online 28 June 2012

Keywords:
Energy payback
Greenhouse gas
Energy Return on Investment
Greenhouse Gas Payback Time
Greenhouse Gas Return on Investment
Photovoltaic
Building integrated photovoltaic

A B S T R A C T

The production of electricity from renewable sources plays a strategic role in the future of energy because it helps to effectively manage climate change through an energy generation portfolio with lower emissions of greenhouse gases.

Photovoltaic solar energy is safe and sustainable and is characterised by a growing trend with a cumulative installed capacity that has reached a total of 40 GW in 2010.

In this paper, investigations are presented using multiple calculations: Energy Payback Time (EPBT), Greenhouse Gas per kilowatt hour (GHG/kWh), Energy Return on Investment (EROI), Greenhouse Gas Payback Time (GPBT) and Greenhouse Gas Return on Investment (GROI). These metrics make it possible to define the energy and environmental performances for a building-integrated photovoltaic system located in Italy.

The module efficiency, the embodied energy and the annual solar irradiance are variables that play a strong role in this analysis. The key parameters include the type of solar cells (e.g., mono-crystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride) and the location where the system is installed (Milan, Rome and Palermo).

The results determine whether solar energy has a viable strategic role in the global energy market.

© 2012 Elsevier Ltd. All rights reserved.

Contents

Abbreviations: AC, Alternating current; a-Si, Amorphous silicon cells; BOS, Balance of System; CdTe, Cadmium telluride cells; CED, Cumulative Energy Demand; CIGS, Copper indium gallium (di)selenide cells; CIS, Copper indium gallium cells; CO_2, Carbon dioxide; $CO_{2\text{-eq}}$, Carbon dioxide equivalent; CPV, Concentrated photovoltaic; c-Si, Monocrystalline cells; Cz-Si, Czochralski silicon; DC, Direct current; EG-Si, Electronic grade silicon; EPBT, Energy Payback Time; EPIA, European Photovoltaic Industry Association; EROI, Energy Return on Investment; GPBT, Greenhouse Gas Payback Time; GROI, Greenhouse Gas Return on Investment; IEA, International Energy Agency; kWh, Kilowatt hour; kWhe, Electrical kilowatt; kWht, Thermic kilowatt; LCA, Life Cycle Analysis; MG-Si, Metallurgical grade silicon; MJ, Megajoule; NPV, Net Present Value; p-Si, Polycrystalline cells; PV, Photovoltaic; r-Si, Ribbon crystalline silicon cells; SiO_2, Silicon dioxide

* Corresponding author. Tel.: +39 0862 434464.
E-mail addresses: federica.cucchiella@univaq.it (F. Cucchiella), idiano.dadamo@univaq.it (I. D'Adamo).

1364-0321/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.04.034

1. Introduction

The market of photovoltaics (PVs) had an extremely high growth trend in 2010 and reached a cumulative installed capacity of 40 GW, of which 60% had been installed between 2009 (7.2 GW) and 2010 (16.6 GW). The Japanese nuclear crisis following its 2011 tsunami has reopened the debate on the future energy mix as much as on the global security of the energy supply; for the renewable energy sector, because of the Kyoto Protocol decrees, there is a growing trend foreseeing that the world oil production by 2050 will be half of that today [1]. Solar energy, especially PV technology, is a competitive component of the electrical power system, especially in the European Union. The achievements of recent years vary from country to country (Table 1) because of several factors, such as the different national policies, incentives and funds availability. The German market (45% of installed capacity) and Italian market (14% of installed capacity) have strongly contributed to the PV installation growth in the EU [2,3].

Today, the technologies for the exploitation of renewable resources are not able to satisfy the primary energy demand and have multiple disadvantages [4,5]:

1. Energy, especially the electricity sector itself, is very capital-intensive and needs more than the average capital investment for the same amount of return on investment that would be expected from other sectors. Moreover, the capital recovery period is also very long and in some cases can be more than 20 years;
2. Production costs are not competitive with fossil fuels;
3. The low efficiency of the system does not allow a significant production of electricity;
4. The intermittent generation does not guarantee a sufficient stability of production, which is essential for the distribution networks.

The most valuable advantage resulting from the installation of a PV system, however, is the pollution emission reduction with respect to systems based on fossil fuel. The amount of carbon dioxide (CO_2) emissions avoided over the life of the system must be the net of the contributions of energy and emissions needed for the production, operation and disposal of the plant, an aspect that defines the incorrect assertion that the environmental impact of such systems is equal to zero [6].

The most important feature of the solar PV systems is that there are no emissions of carbon dioxide – the main gas responsible for global climate change – during their operation; while indirect emissions of CO_2 occur at other stages of the life cycle, these are significantly less than the avoided emissions. Remarkably, some authors do not incorporate the emissions from these phases, resulting in poorly calculated avoided CO_2 emissions [7].

The Life Cycle Analysis (LCA) evaluates the environmental impacts of a product or process from production to disposal. A LCA investigates the material and energy inputs required to produce and use a product, the emissions associated with its use, and the environmental impacts of disposal or recycling. The LCA may also investigate external costs, such as environmental mitigation, that are made necessary by the production or use of a product [8–10].

Fthenakis and Kim [11] evaluate the environmental benefits of solar technology by comparing it with other energy sources and, moreover, identifying the main phase in which the greenhouse gas emission is the greatest (Table 2). For example, the GHG emissions from the nuclear-fuel cycle are mainly related to the fuel production (75%) (i.e., mining, milling, fabrication, conversion and enrichment of uranium fuel).

This paper is organised into different sections: in Section 2, the most advanced PV technology and the characteristics of different cell types are presented. In Section 3, an overview of the different LCA methods utilised are presented. The energetic and environmental impacts of various PV types, located in various places, are evaluated. In Section 4, the technical parameters of a roof-

Table 1
Installed PV capacity (MW).
Source: [2].

Country	Market 2009	Market 2010	Cumulative 2010
Germany	3806	7408	17,193
Italy	717	2321	3494
Spain	17	369	3784
Czech Republic	398	1.490	1953
France	219	719	1025
Belgium	285	424	803
Japan	483	990	3622
USA	477	878	2528
APEC	258	342	1191
China	228	520	893
Total	**7257**	**16,498**	**39,531**

Table 2
Comparison of GHG emissions from PV with those from conventional fuel-burning power plants.

Technology	$gCO_{2\text{-eq}}$/kWh	Critical phase	% GHG in critical phase with respect to total emission	Reference
Coal	1210	Operation[a]	88	[12]
Natural Gas	760	Operation[a]	67	[12]
Petroleum	880	Operation[a]	74	[12]
Nuclear	24	Fuel production[b]	75	[13]
Photovoltaic (CdTe)[d]	24	Materials[c]	100	[14]
Photovoltaic (c-Si)[e]	37	Materials[e]	100	[15]

[a] Plant operation from the amount of fuel used for start-up of the auxiliary steam generators and in-plant heating, along with the plant's annual running expenses.
[b] Fuel production i.e., mining, milling, fabrication, conversion, and enrichment of uranium fuel.
[c] Stage to produce materials comprising PV system.
[d] Based on ground-mount installation, average US insolation of 1800 kWh/m^2/year and performance ratio of 0.8.
[e] Based on the Southern European insolation, 1700 kWh/m^2/year and a performance ratio of 0.75.

Nomenclature

A_{cell}	active surface (m^2/kWp)
dE_f	decrease of generator efficiency
E_{BOS}	embodied energy of BOS
E_D	energy requirements for decommissioning, disposal or other end-of-life
E_F	embodied energy of PV module fabrication
E_{IN}	embodied energy of the system
$E_{IN/A}$	embodied energy of the system per unit effective area
E_{OUT}	energy output of the system
$E_{OUT,1}$	annual energy output of the system during the 1st year
$E_{OUT,GLB}$	total energy output of the system during all the life cycle
E_P	embodied energy of silicon purification and processing
E_S	embodied energy of silicon ingot slicing
E_T	energy for transport of PV modules from factory to installation site
F_{MIXE}	mix of electricity
GHG/kWh	greenhouse gas for kilowatt hour
GHG_D	emissions for decommissioning and disposal of cells at end of lifetime
GHG_{EM}	emission of life cycle photovoltaic electricity production
GHG_M	emissions of manufacturing phase of PV system
GHG_{OM}	emissions during the operations of maintenance
GHG_{SV}	GHG produced by the local power plant for the power generated by PV
$GHG_{SV,GLB}$	annual GHG produced by the local power plant
GHG_T	emission to transport PV modules from factory to installation site
K_f	optimum angle of tilt
MJ_{el}	electrical energy
MJ_{prim}	primary energy
N	lifetime of a PV module
η_f	number of PV modules to be installed
P_f	the nominal power of a photovoltaic module
t_r	average annual insolation (kWh/m^2)
ψ_f	module efficiency
ψ_{BOS}	BOS efficiency

mounted PV system are analysed. In the following Sections 5–9, the PV efficiency is evaluated through five indicators. The energy required for the product life cycle is evaluated through the Cumulative Energy Demand (CED), while the energy produced by a PV system is estimated using several technical parameters and PV technology. Some concluding remarks close the paper (Section 10).

2. State-of-the-art photovoltaic technology

This section presents a description of the technological, economic and environmental aspects of a roof-mounted PV system.

A PV system uses one or more solar panels to convert sunlight into electricity and can be classified in multiple ways [16–18]:

- grid-connected centralised;
- grid-connected decentralised;
- off-grid non-domestic;
- off-grid domestic;

A grid-connected energy system is a power system that is connected to an electricity transmission system and a distribution system; off-grid solar electric homes offer comfortable lifestyles with 1–3 kW solar electric systems. The solar cells that characterise a PV system are made of the same kinds of semiconductor materials, such as silicon, used in the microelectronics industry. For solar cells, a thin semiconductor wafer is specially treated to form an electric field, positive on one side and negative on the other. When light energy strikes the solar cell, electrons are dislocated from the atoms in the semiconductor material. If the electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons can be captured in the form of an electric current—that is, electricity. This electricity can then be used to power a load, such as a light or a tool [19]. A solar inverter or PV inverter is a critical component in a PV system. It performs the conversion of the variable DC output of the PV modules into a utility frequency AC current that can be fed into the commercial electrical grid or used by a local, off-grid electrical network. An inverter allows the use of ordinary mains-operated appliances on a direct current system. The solar inverters have special functions adapted for use with the PV arrays, including maximum power point tracking and anti-islanding protection.

The PV systems can be classified for the type of cells used:

- *silicon based*, such as monocrystalline (c-Si), polycrystalline (p-Si), ribbon crystalline silicon (r-Si), amorphous silicon (a-Si);
- *non-silicon based*, such as cadmium telluride (CdTe), copper indium (gallium) or diselenide (CIS or CIGS);
- *new concept devices*, such as concentrated PV (CPV).

There are three general families of PV modules on the market today. They are single crystal silicon, polycrystalline (multicrystalline) silicon, and thin film [20].

The crystalline silicon PV technology was first developed based on silicon wafers and is known as the 1st generation solar technology. The silicon-based technology is technically proven and reliable and has succeeded in achieving market penetration, primarily in off-grid remote areas and in grid-connected applications where sufficient subsidies are available to offset its high cost. There are several inherent limitations to this 1st generation, however. The silicon wafers are fragile, making the processing difficult and limiting the potential applications. The process is very labour and energy intensive, and the manufacturing plant capital costs are high, limiting the scale-up potential. Because materials represent more than 60% of the manufacturing costs and because the silicon supply is finite, the long-term potential for cost reduction is insufficient to deliver broadly affordable energy [21].

To simplify manufacturing and reduce costs, a 2nd generation (known as thin film technologies) was developed [22]. These technologies are typically made by depositing a thin layer of photo-active material onto glass or a flexible substrate, including metal foils, and they commonly use a-Si, CIGS or CdTe as the semiconductor. Thin film PV is less subject to breakage when manufactured on a flexible foil. However, the promise of low-cost power has not been realised, and the efficiency remains lower than that of the 1st generation solar technology. Some questions also remain regarding the toxic legacy of the materials, both in the manufacturing and at the end of their life.

The 3rd generation solar technologies have been estimated to achieve higher efficiencies and lower costs than the 1st or 2nd

Table 3
Review of cell/module efficiency for different PV technologies and value selection.

Module PV	Cell efficiency (%)			Module efficiency (%)			Module selected value (%)
Monocrystalline silicon	14–19	15.3	16–22	16	14	13–19	16
Polycrystalline silicon	13–17	14.4	14–18	14	13	11–15	13
Ribbon crystalline silicon	14–16	13.1	–	12	11	–	11.5
Amorphous silicon	6–8	6.5	4–8	6	7	4–8	6
Cadmium telluride	7–11	7.6	10–11	8	10	10	9
Copper indium gallium selenide	8–13	10.7	7–12	10	10	7–12	9.5
Reference	[25]	[26]	[23]	[25]	[15]	[23]	

generation technologies. The 3rd generation approaches being investigated include dye-sensitised titanium solar cells, organic PV, tandem cells, and materials that generate multiple electron–hole pairs [23,25].

The performance of a PV can be described in terms of its energy conversion efficiency. The cell efficiency measures the percentage of the incident solar energy (input) that the cell converts into electricity under the standard rating conditions [24]. The overall electrical efficiency of the PV module can be increased by increasing the packing factor and decreasing the temperature of the PV module. Table 3 presents a literature review of the conversion efficiency and efficiency correction coefficient of the cell and the modules with different production technologies [25].

The module efficiency values used in this paper (last column of Table 3, "Selected value") are the average of the two extreme values identified by a literature review and are the values used in the analysis of the present paper.

Multi-junction solar cells are solar cells containing several junctions. Each junction is tuned to a different wavelength of light, reducing one of the largest inherent sources of losses and thus increasing efficiency. The traditional single-junction cells have a maximum theoretical efficiency of 34%; a theoretical "infinite-junction" cell would improve this to 87% under highly concentrated sunlight [27]. Currently, the best lab examples of traditional silicon solar cells have efficiencies of approximately 25%, while the European Photovoltaic Industry Association (EPIA) [23] estimates that the multi-junction cells have a performance efficiency of more than 42%, a value greater than that in Table 3.

Innovations are developing relatively quickly in the world of 3rd generation solar cells, and they could begin to see commercial applications within next years; for the 1st and 2nd generation solutions, there will probably be constant growth [16].

3. Energetic and environmental metrics: state-of-the-art

The policies designed to improve the energy efficiency and development of renewable sources allow us to integrate the economic and environmental objectives [28]. The integration of the environmental and economic goals is a phenomenon in rapid growth, particularly for those sectors and activities where the environmental impact is particularly relevant.

The installed PV capacity has grown at a rate of 40% during the last decade. As the industry has grown, the PV module prices declined along a well-established learning curve, which has seen cost reductions of 22% for each doubling of the cumulative capacity, during the last few decades. The learning curve has since returned towards its historic trend, and the global installation capacity increased to 10 Gigawatt-peak/annum in 2010. The International Energy Agency (IEA) and the EPIA expect further cost reduction with increased production capacities, improved supply chains and economies of scale. The technological cost reduction opportunities include improvements in efficiency for the different cell types. Based on these drivers, the IEA and EPIA have made cost projections using learning rates of 18%, slightly less than the historical average of 22% [29–31].

The Life Cycle Cost analysis demonstrates that the PV systems based on c-Si and p-Si technologies require a higher initial cost but also produce a higher Net Present Value (NPV) [25].

A comprehensive literature study has been made to individualise the possible metrics that can be used to evaluate the investment in the PV system. The profitability of PV systems has been the subject of many articles, but these evaluations are always limited to the use of two possible metrics: EPBT and GHG/kWh. The literature results for these two metrics are presented in the two following sub-sections. However, this study contributes the findings of the PV evaluation not only with these two indicators but also with EROI, GPBT and GROI. With these additional metrics, a state-of-the-art system that is not available cannot be presented, but metric descriptions can be made. The estimated values of all the metrics are directly presented in the following sections: EPBT (Section 5), GHG/kWh (Section 6), EROI (Section 7), GPBT (Section 8) and GROI (Section 9).

3.1. Energy Payback Time

The energy balance of a PV system is expressed by the EPBT, which is the time it takes for the PV system to generate the amount of energy equal to that used in its production [32]. The EPBT depends on multiple factors: cell technology, type of encapsulation, frame and array support, module size and efficiency, PV system application type (autonomous or grid-connected) and the PV system performance as determined by the irradiation and the performance ratio. The EPBT is also affected by factors that do not directly relate to the characteristics of the PV power system itself; the conversion efficiency of the electricity supply system and the energy requirements of materials like glass, aluminium and others [33]. The EPBT presents high variability depending on the type of technology. The EPBT for a standard, single-crystalline module PV system is two years. For the PV systems using multicrystalline modules produced by the casting method, the EPBT is calculated as 1.7 years. The PV systems with modules produced using the ribbon method reduced the EPBT to 1.5 years. For the thin-film module-based PV systems, there are several types of thin-film PV technologies – the most common are amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium diselenide (CIS), and copper indium gallium diselenide (CIGS) – and previous studies highlight CdTe modules, which have an EPBT of 1.0 year.

With respect to the processes for producing PV systems, different EPBT values can be observed [10,34]. The EPBT associated with PVs formed from silicon produced with the Siemens process was 4 years in 2001 and 1.5 years in 2011.

Fthenakis and Kim [11] recently investigated the GHG emissions and EPBT of the CdTe PV modules, including the raw

material extraction and transportation from when the module is assembled to recycling (®). They estimate a 10% EPBT reduction. Ultimately, the EPBT is largely determined by the Balance of System (BOS) components; generally, it contributes for 0.3 years, the system supports contribute for 0.1 years, and the remainder is due to modules (Table 4). In the table, the EU utilises the rooftop-mounted PV systems for European production and installation under the Southern European irradiation of 1700 kWh/m^2 and a performance ratio of 0.75. The US utilises ground-mounted PV systems for American production, with an average annual insolation of 1800 kWh/m^2 and a performance ratio of 0.8.

Laleman et al. [35] present the results of a comparative analysis among the PV systems located in different nations. The range of the EPBT is 2–3 years in Spain (1282 kWh/kWp), 3–4 years in Switzerland (848 kWh/kWp), and 4–5 years in Belgium and United Kingdom (725 kWh/kWp). These values are related through the modules realised according the c-Si technology; using the thin-film technology, in the location with a lower irradiation, the EPBT is less than 1 year, and in the location with higher irradiation, it is 0.5 years.

Using the primary energy requirements in conjunction with the annual yields to calculate the EPBT for various locations throughout the country, the values of EPBT in Malaysia for various technologies at different locations show that the EPBT of thin film rooftop systems is in the range of 1.89–2.6 years, which is the smallest compared to that of the monocrystalline and polycrystalline rooftop systems. Thus, the thin films are recommended for use in Malaysia [36].

Hall et al. [37] conducted an economic and environmental analysis of the PV modules installed in Spain. They monetised the energy-environmental benefits derived during the entire lifetime of the PV modules to determine the total financial benefits of the PV system. The environmental analysis demonstrates the integrity of the grid-connected PV systems, obtaining recuperation times for the energy that vary between 2.5 (thin-film *ground*) and 3.6 years (p-Si *ground*).

The EPBT values of these studies are for thin-film, module-based PV systems. There are several types of thin-film PV technologies – the most common are a-Si, CdTe, CIS, CIGS – and the EPBT values are not constant for different technologies.

Raugei et al. [38], under the hypothesis of an average annual insolation of 1700 kWh/m^2 in Southern Europe, estimate an EPBT of 2.8 years with the CdTe modules and 1.5 years with CIS. The nominal conversion efficiencies of the modules are 9% for CdTe and 11% for CIS, while that of poly-Si modules was assumed to be 14%.

To evaluate the EPBT of a PV system, it is necessary to have knowledge of embodied energy from the resource extraction through the manufacturing and to the production use until the end of the life. Generally, the previous studies analysed do not take into account the consequences of the transportation and disposal phases. The real PV impact when long distances must be covered (i.e., Italy, where the PV production is much less than the demand, and it must be imported) could be interesting to evaluate. The disposal phase is also important to analyse to evaluate its influence on the energy and emissions analysis [39].

If estimated correctly, the EPBT is a powerful metric that captures both the upstream costs and the use-phase capabilities of a PV [40]:

$$\mathrm{EPBT} = \frac{E_{\mathrm{IN}}}{E_{\mathrm{OUT}}} \tag{1}$$

where E_{IN} is the embodied energy of the system and BOS (kWh) and E_{OUT} is the annual energy output of the system (kWh/y).

The embodied energy is divided into two categories (embodied energy of the system and of the BOS). The first category is defined by several factors: the embodied energy of silicon purification and processing (E_{P}); the embodied energy of silicon ingot slicing (E_{S}); the embodied energy of PV module fabrication (E_{F}); the energy for transport of PV modules from factory to installation site (E_{T}); and the energy requirements for decommissioning and disposal or other end-of-life energy (E_{D}).

The BOS is also a factor affecting the embodied energy calculation (E_{BOS}). When the embodied energy of a PV system is analysed, the PV module itself is not the only item to be considered, even though it contributes to the greatest amount of energy. Others components are called the BOS, including the electrical BOS components and the mechanical BOS components. The electrical BOS components include the inverters, electrical wirings and electronic control devices, while the mechanical BOS components include the mounting materials and structures.

The embodied energy of the system is given by

$$E_{\mathrm{IN}} = E_{\mathrm{P}} + E_{\mathrm{S}} + E_{\mathrm{F}} + E_{\mathrm{BOS}} + E_{\mathrm{T}} + E_{\mathrm{D}} \tag{2}$$

$$E_{\mathrm{OUT}} = t_{\mathrm{r}} K_{\mathrm{f}} \psi_{\mathrm{F}} \psi_{\mathrm{BOS}} A_{\mathrm{cell}} \frac{P_{\mathrm{f}}}{1000} \eta_{\mathrm{f}} \tag{3}$$

where t_{r} is the average annual insolation; K_{f} is the optimum angle of tilt; ψ_{f} is the module efficiency; ψ_{BOS} is the BOS efficiency; A_{cell} is the active surface; P_{f} is the nominal power of a PV module; and η_{f} is the number of PV modules to be installed.

3.2. Greenhouse gas per kilowatt hour

According to the Kyoto protocol, "GHG" covers six categories of greenhouse gases (CO_2, CH_4, N_2O, HFC, PFC, SF_6) and is estimated using the CO_2 equivalent ($CO_{2\text{-eq}}$), a metric used to compare the emissions from various greenhouse gases based upon their global warming potential. In the previous section, the range of values of the GHG/kWh of PV technology is determined to be much lower than other energy sources. These values differ between the various nations and also according to the energy mix of a given nation that characterises each of the different processing methods that relate to the different PV technologies [13]. The compared studies concluded that the GHGs can exist within a large range of $gCO_{2\text{-eq}}$ because it depends on several conditions.

Table 4
Module conversion efficiency, Energy Payback Period and Greenhouse Gas Emissions.

Technology PV	Efficiency (%)	Production	Recycling	EPBT (years)	GHG ($gCO_{2\text{-eq}}$/kWh)
r-Si	11.5	EU	–	1.7	30
p-Si	13.2	EU	–	2.2	37
p-Si	13.2	EU	®	1.9	Not defined
c-Si	14.0	EU	–	2.7	45
c-Si	14.0	EU	®	2.5	Not defined
CdTe	8.0	EU	–	1.0	21
CdTe	9.0	US	–	1.1	24

In Bravi et al. [33], the direct and indirect emissions associated with PVs and electricity generation are evaluated focusing on the GHG emissions related to the different solar module production in the period of 2000–2009. The emissions associated with the PV systems vary considerably: 76 $gCO_{2\text{-eq}}$/kWh for p-Si modules; 73 $gCO_{2\text{-eq}}$/kWh for c-Si; 23 $gCO_{2\text{-eq}}$/kWh for thin-film; and 15 g $CO_{2\text{-eq}}$/kWh for a generic PV system.

Fthenakis and Kim [11] recently investigated the GHG emissions and the EPBT of CdTe PV modules based on U.S. production and insolation conditions (insolation = 1800 kWh/m^2/year; performance ratio 0.8; lifetime of 30 years). Their estimates were 24 $gCO_{2\text{-eq}}$ kWh of GHG emissions and 1.1 years for the EPBT of the ground-mounted installations. The life cycle energy uses and the GHG emissions over the complete life cycle of the PV BOS were determined to be 5–6 $gCO_{2\text{-eq}}$/kWh and 2–3 $gCO_{2\text{-eq}}$/kWh for the structure supports.

The Siemens production process has had a successful renewable energy policy that has enabled significant progress to be made towards the greenhouse gas emissions reduction. This has also achieved the best performance of the p-Si modules (from 33 $gCO_{2\text{-eq}}$/kWh in 2007 to 21 $gCO_{2\text{-eq}}$/kWh in 2011) [34]. To reduce the GHGs an additional 20% (in terms of $gCO_{2\text{-eq}}$/kWh), the 91% of PV-grade silicon is made using the traditional Siemens process, with the remaining 9% created from the fluidised bed reactor process. The GHG emissions normally occur during the manufacturing, installation and transportation phases of the solar PV modules. The GHG emissions pertaining to the renewable sources have to be lower than those of fossil fuels. Only in this way is it possible to supply a significant proportion of the energy needs, creating many public benefits for the nation and for states and regions, including in the forms of environmental improvement, increased fuel diversity and national security, and regional economic development benefits [15]. While the accurate calculation of GHG emissions per kilowatt-hour (kWh) is often difficult, sound knowledge of the life cycle GHG emissions can be an important indicator for the mitigation strategies in the power sector.

This value can be estimated according the following equations:

$$\mathrm{GHG/kWh} = \frac{\mathrm{GHG_{EM}}}{\mathrm{GHG_{OUT,GLB}}} \tag{4}$$

$$\mathrm{GHG_{EM}} = \mathrm{GHG_M} + \mathrm{GHG_{OM}} + \mathrm{GHG_T} + \mathrm{GHG_D} \tag{5}$$

$$E_{\mathrm{OUT,GLB}} = \sum\nolimits_{T=1}^{N} E_{\mathrm{OUT},T} \tag{6}$$

$$E_{\mathrm{OUT},T} = E_{\mathrm{OUT},T\text{-}1} - E_{\mathrm{OUT},T\text{-}1}\, dE_{\mathrm{f}} \tag{7}$$

where the $\mathrm{GHG_{EM}}$ (GHG emitted) are the emissions associated with the life cycle PV electricity production ($gCO_{2\text{-eq}}$); $\mathrm{GHG_M}$ (GHG manufacturing) are emissions related to the manufacturing phase of a PV system; $\mathrm{GHG_{OM}}$ (GHG operations maintenance) are emissions during the operations of maintenance; $\mathrm{GHG_T}$ (GHG transport) are the emissions related to the transport of the PV modules from the factory to the installation site; $\mathrm{GHG_D}$ (GHG disposal) are the emissions for the decommissioning and disposal of the cells at the end of their lifetime; $E_{\mathrm{OUT,GLB}}$ is the total energy output of the system during all of the life cycle (kWh); dE_{f} is the decrease of the generator efficiency (%); and $E_{\mathrm{OUT,1}}$ is the annual energy output of the system during the 1st year and is estimated according to Eq. (3).

3.3. Energy return on investment

One technique for evaluating the energy systems is the net energy analysis, which compares the amount of energy delivered to society by a technology to the total energy required to find, extract, process, deliver, and otherwise upgrade that energy to a socially useful form. The Energy Return on Investment (EROI) is the ratio of energy delivered to energy costs. In the case of electricity generation, the EROI entails the comparison of the electricity generated to the amount of primary energy used in the manufacturing, transport, construction, operation, decommissioning, and other life cycle stages of the facility. It is a relevant extension of the EPBT and is estimated as follows [41]:

$$\mathrm{EROI} = \frac{E_{\mathrm{OUT,GLB}}}{E_{\mathrm{IN}}} \tag{8}$$

When the ratio is less than one, the PV system is not useful because the amount of energy delivered to the society is less than the total energy required to produce it [37].

3.4. Greenhouse Gas Payback Time

The Greenhouse Gas Payback Time (GPBT) is a measure of the years necessary for a PV system to balance the emission of greenhouse gases, and it is estimated as follows [42]:

$$\mathrm{GPBT} = \frac{\mathrm{GHG_{EM}}}{\mathrm{GHG_{SV}}} \tag{9}$$

$$\mathrm{GHG_{SV}} = E_{\mathrm{OUT}} F_{\mathrm{MIXE}} \tag{10}$$

where the GHGs saved ($\mathrm{GHG_{SV}}$) are the annual GHGs produced by the local power plant for the power generated by the PV system ($gCO_{2\text{-eq}}$/yr) and the F_{MIXE} emission factor is the portion of different materials used in the electricity production, also known as the mix of electricity ($gCO_{2\text{-eq}}$/kWh).

3.5. Greenhouse Gas Return on Investment

The Greenhouse Gas Return on Investment (GROI) metric is as a complimentary ratio to EROI. Unlike this last one, the GROI accounts for the life cycle energy mix, for the efficiency, circularity, and supply chain of energy distribution, and for the energy offset by a new energy installation. It is calculated as the technology lifetime divided by the GHG payback time (GPBT) [43]:

$$\mathrm{GROI} = \frac{\mathrm{GHG_{SV,GLB}}}{\mathrm{GHG_{EM}}} \tag{11}$$

$$\mathrm{GHG_{SV,GLB}} = \sum_{T=1}^{N} \mathrm{GHG}_{\mathrm{SV},T} \tag{12}$$

The $\mathrm{GHG_{SV,GLB}}$ are the emissions prevented by installing the new electricity capacity, whether it is the marginal emissions from a power plant or the life cycle emissions of an alternative installation ($gCO_{2\text{-eq}}$).

In this paper, an attempt has been made to calculate the energetic and environmental benefits of a PV system according to the five metrics (EPBT, GHG, EROI, GPBT, GROI) previously described.

4. System description and findings

The following analyses are related to a normalised roof-mounted PV system installed in three different cities in north, central and south Italy. The previous indicators are estimated for the system in such a way that both the energetic and environmental aspects are investigated.

More options are analysed within the range of technologies, including the wafer-based silicon and a variety of thin film technologies. The range of current technologies and possible future options have been grouped from the current first generation to future third generation technologies. The commonly used

Table 5
Main technical characteristics of PV system.

Variables		Reference	Reference value			
Average annual insolation (kWh/m^2)	t_r	[44]	Milan 1.383	Rome 1.511		Palermo 1.623
PV module efficiency (%)	ψ_f	Table 3	CdTe 9	CIS 9.5	p-Si 13	c-Si 16
Active surface (m^2/kWp)	A_{cell}	[35]	CdTe 10	CIS 10	p-Si 8	c-Si 7
Optimum angle of tilt[a]	K_f	[44]	Table 6			
BOS efficiency[b]	ψ_{BOS}	[45]	85%			
The nominal power of a photovoltaic module	P_f	[41]	200 Wp			
Number of PV modules to be installed	η_f	[46]	Variable			
Lifetime of a PV module[c]	N	[46]	20			

[a] The optimal value is not a fixed value and depends by tilt angle and orientation (here south 30°).
[b] Including inverter efficiency = 95% and other factors = 90%.
[c] The project lifetime is fixed equal to the Feed in Premium (FiP) contributes.

Table 6
Correction coefficient for evaluation of PV electrical power.

Orientations	Tilt angle				
	20°	**30°**	**45°**	**60°**	**90°**
0° (south)	1.11	1.13	1.11	1.03	0.75
±15°	1.10	1.12	1.11	1.03	0.76
±15°	1.10	1.12	1.11	1.03	0.76
±30°	1.09	1.11	1.10	1.03	0.78
±45°	1.07	1.09	1.08	1.02	0.79
±60°	1.05	1.06	1.04	0.99	0.79
±90°	0.99	0.97	0.94	0.88	0.70

Table 7
Review of conversion factor of electricity in primary energy.

C (MJ_{el}/MJ_{prim})	**Geographical area**	**Reference**
0.31	Western Europe	[11]
0.35	Not specified	[35]
0.38	Not specified	[49]
0.40	Italia	[50]

Table 8
Review of embodied energy for monocrystalline PV system ($kWht/m^2$).

		Reference		
		[35]	[47]	[44]
Silicon purification and processing	E_P	666	666	670
Silicon ingot slicing	E_S	120	120	120
Module fabrication	E_F	190	190	190
BOS	E_{BOS}	358	475	482
Transport PV from factory to installation site	E_T	26	–	54
Decommissioning and disposal	E_D	0	–	0
E_{IN} ($kWht/m^2$)		**1360**	**1451**	**1516**

technologies are p-Si and c-Si; CIS and CdTe are the modules for the future.

Italy is characterised by different levels of solar insolation, and for this reason, the analyses of the PV systems are based on systems located in north, central and south of Italy (Milan, Rome and Palermo).

The PV system is installed on a roof, and the performance is affected by temperature, solar insolation, shading, temperature, module efficiency, inverter and other elements performances (Table 5). For a grid-connected system that aims to generate the maximum amount of energy on an annual basis, the tilt angle should be at the local latitude. The off-grid systems are usually designed to maximise output in winter, when the power need is the greatest, so the tilt angle should be at the local latitude plus 10°. For the evaluation of the annual production capability of electric power of a PV installation, usually the correction coefficients of Table 6) are applied to the annual mean radiation on the horizontal plan .

5. Energy Payback Time: estimation and results

The EPBT can be affected by the installation location differences, such as the circularity, electricity supply chain, distribution losses, consumer needs, and regional electricity capacity. For the estimation of this metric, the two variables related to Embodied energy (E_{IN}) and Energy Output (E_{OUT}) need to be first estimated.

5.1. Embodied energy estimation

To examine the energy efficiency, the LCA approach is used. The LCA is an instrument to quantify all impacts of the entire energy supply chain. To obtain the CED for production, the entire facility has to be split into components, sub-components and their respective materials. Using this material balance with specific data for energy and emissions, the CED can be calculated [35]. Normally the energy is defined as the primary energy (MJ_{prim}) that had to be converted into electrical energy (MJ_{el} = MJ) according to the proper conversion factor [47] that measures the efficiency of energy production in a region (Table 7). In this paper, for the conversion from primary to electrical energy, we used the equivalence 9MJ_{prim} = 3.6 MJ = 1 kWhe (electrical kilowatt, kWhe = kWh) or 2.5 kWhe = 1 kWht (thermic kilowatt). Some authors proceed having not incorporated this factor into the analysis, and this leads to a significant distortion; in fact, the results of the EPBT are approximately 3 times greater than in scenarios where it is considered [48].

On the issues addressed, there are several academic papers that analyse the embodied energy of a PV system. Depending on these values, calculated with the CED methodology, the numerator of EPBT ratio can be quantified (Table 8). The energetic inputs for a PV system are given by the energy required during the phases of raw material extraction, transport, production, installation, management and recycling. There is a growing body of literature that directly calculates the embodied energy of the several phases inside the entire life cycle. This paper will use the existing literature values as a starting point for the scenario inputs for the embodied energy of the PV cells, modules and arrays. More specifically, a literature review has emphasised the situation in Table 8 [1,51]. In the table are the values used by several authors: the embodied energy of silicon purification and processing (E_P); the embodied energy of silicon ingot slicing (E_s); the embodied energy of PV module fabrication (E_F); the embodied

energy of the BOS (E_{BOS}); the energy to transport PVs from factory to installation site (E_T); and the energy required for decommissioning and disposal (E_D)

Next, the estimated values of E_P, E_s, E_F, E_{BOS}, E_T and E_D are described as to how they are used in the present paper for the subsequent analyses required to evaluate the environmental and energetic conveniences of PV systems. Meanwhile, some processes contribute to a large portion of the embodied energy, while some processes consume very little energy. Starting with the values of the previous research studies, these values are estimated but are never set equal to zero. The final scope is to define a reference situation that accurately describes a real PV system where, if also with a small contribution, all of the processes requiring the use of energy within the entire life cycle are taken into account.

The silicon purification and processing requires three steps. First, the metallurgical grade silicon (MG-Si) is created by the carbothermic reduction of silicon dioxide (SiO_2), 'quartz sand'. It is a process in which coal, coke and wood chips are heated together with SiO_2. The energy required to produce 1 kg of (MG-Si) is 20 kWh. Second, the electronic grade silicon (EG-Si) is produced from the MG-Si. The energy required to produce 1 kg of EG-Si is 100 kWh, and there is a 90% yield. The next step is to melt the EG-Si in a Czochralski crystal puller at 1400 °C and to slowly crystallise the silicon to form a single crystal ingot of silicon. There is a total yield of 72% from the Czochralski process. The energy required to produce Czochralski silicon (Cz-Si) is 290 kWh/kg. Thus, the embodied energy required for 1 m^2 PV systems is 1448 kg of the single crystalline silicon.

The embodied energy required for the silicon purification and processing for 1 m^2 of the PV systems is calculated as follows (E_p):

I phase	Production of 2234 kg MG-Si $= 20 \times 2234 = 44.68 \approx$	45 kWh	
II phase	Production of 2011 kg EG-Si $= 100 \times 2011 = 201.1 \approx$	201 kWh	(13)
III phase	Production of 1448 kg Cz-Si $= 290 \times 1448 = 419.92 \approx$	420 kWh	
	Total(E_P)	666 kWh	

For the wafer production, the ingot obtained from Czochralski process is sliced into wafers. The solar cell fabrication entails a sequence of high-temperature diffusion, oxidation, and deposition and of anneals steps. The energy required to prepare 1 m^2 of silicon cell is 120 kWh.

$$E_S = 120\ \text{kWht/m}^2 \tag{14}$$

The solar cells are encapsulated between a glass front plate and back cover foil of tedlar through heat and pressure and then hermetically sealed using state-of-the-art technology. The module is then framed with anodised aluminium channels on the perimeter of the module. These are manufactured to withstand all climatic conditions.

$$E_F = 190\ \text{kWht}/m^2 \tag{15}$$

The BOS *embodied energy* estimated by Yang and Blyth [53] is less than that estimated by Radhi [52] because there is no consideration of the contribution of batteries and the energy required for the support structure that are evaluated as not relevant. For a roof-mounted PV system, the required energies are 200–278 kWht/m^2 for the support structure, 46 kWht/m^2 for the battery, and 33 kWht/m^2 for the inverter (e.g., for the electronic components, cables, miscellaneous).

If the PV system is ground mounted, the total BOS embodied energy is 734 kWht/m^2, of which 500 kWht/m^2 are required by the support structure [51]. In the present paper, the embodied energy of the support structure (estimated from 200 to 278) is defined as equal to the average value of the above values.

$$E_{BOS} = (239+46+33+125)\text{kWht/m}^2 = 443\ \text{kWht/m}^2 \tag{16}$$

The energy required to transport the PV modules from the factory to the installation site depends on the individual situations, especially in Italy, where the PV production is much lower than the demand, and it must be imported from abroad. In this paper, we have chosen the average of those proposed in Table 8.

$$E_T = 40\ \text{kWht/m}^2 \tag{17}$$

The decommissioning, disposal or other end-of-life energy requirements of PV modules (E_D) are underestimated in most of scientific papers. The recycling stage of the silicon PV modules that encompasses the module collection, disassembly of frames and cables, shredding, and material separation is also investigated in the present paper, and according Kim and Fthenakis [49], it is quantified as 1.7% of E_{IN}.

$$E_D = 25\ \text{kWht/m}^2 \tag{18}$$

The values identified in the previous formulas are related to the c-Si roof-mounted PV system and represent the individual contributions of the embodied energy per unit effective area (QUOTE):

$$E_{IN/A} = (666+120+190+443+40+25)\text{kWht/m}^2 \times 0.40\ \text{kWht/m}^2 = 594\ \text{kWht/m}^2 \tag{19}$$

$$E_{IN} = E_{IN/A}A_{CELL} = 4158\ \text{kWh} \tag{20}$$

According to the obtained result, the distribution of the embodied energy in the case of the PV system is presented in Fig. 1. The percentage of the embodied energy of the PV modules system is approximately 66%; the BOS energy is 30%. The energy for the transportation and decommissioning is 4.4%.

The E_{IN} must be defined not only for the c-Si technology but also for the cases of p-Si, CdTe and CIS.

With regard to the c-Si technology, the estimation of this value (according to Eq. (20) is equal to 4158 kW) is obtained through the following steps (Table 9):

Step 1. Identification though a literature analysis of embodied energy values, estimated with the CED methodology and expressed as the primary energy per unit area [35];
Step 2. Electrical energy input is converted into the primary energy requirements with the proper efficiency factor (Table 7);
Step 3. Conversion from MJ to kWh;
Step 4. Estimation of the value of the embodied energy per unit of effective area ($E_{IN/A}$=594 kWh/m^2 from Eq. (19)). This estimated value has a deviation of 43 kWh/m^2 with respect to the literature value (551 kWh/m^2). To not overrate the PV system performance, this incremental energy correction is also applied to the other technologies;
Step 5. Determination of the E_{IN} value given by the product obtained in the previous step and the value of an active surface (Table 5).

According to these steps, the E_{IN} values are also estimated for the p-Si, CdTe and CIS technologies. The values are increased for the deviation amount identified for the c-Si technology. Indeed, step 4 of previous analyses identifies a c-Si deviation that cannot be verified for the other technologies. No other studies present an E_{IN} quantification for the other technologies. Because we cannot proceed with the deviation quantifications in all the cases, a possible way to proceed is to use the values of Laleman et al. [35] as a starting point and to apply the same deviation value for all of

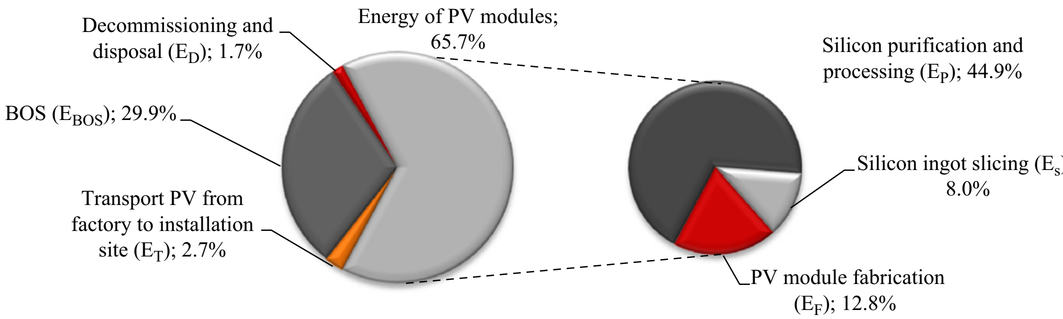

Fig. 1. Embodied energy used in the rooftop BIPV system.

Table 9
Embodied energy (E_{IN}) based on technology used.

Step	Step 1	Step 2	Step 3	Step 4	Step 5
	MJ_{prim}/m^2	MJ_{el}/m^2	kWh/m^2	kWh/m^2	kWh
c-Si	5670	1985	551	594	4158
p-Si	4720	1652	459	502	4016
CdTe	2200	770	214	257	2570
CIS	3170	1110	308	351	3510

Table 10
E_{OUT} of PV system located in Milan, Rome and Palermo (kWh/yr).

	PV cells type			
	CdTe	CIS	p-Si	c-Si
Milan	1196	1262	1382	1488
Rome	1306	1379	1509	1625
Palermo	1403	1481	1621	1746

the technologies correcting the values for the same amount. The relevance of the paper is given by the simultaneous comparison of all 4 technologies. In this paper, the embodied energy is estimated according the described procedure. Moreover, only for the c-Si technology is a detailed analysis presented with respect to the input of the analysis; for the other technologies, only the final value is presented. The deviation of 43 kWh/m^2 may presumably be considered fixed for the remaining technologies (column step 4 Table 9).

5.2. Energy output estimation

The annual energy output of the PV system depends on the type of technology and the technical parameters of the system. This paper analyses a normalised roof-mounted PV system with an orientation that is facing south and an inclined angle of 30°. With respect to the location, three situations are analysed relative to the cities of Milan, Rome and Palermo. The position with the maximum correction factor has been chosen. The previously analysed Eq. (3) is used for the estimation of this variable.

The calculated results, classified for the three Italian locations, are in Table 10.

5.3. EPBT estimation and discussion

Energy Payback Time is affected by location where the PV is located and by the type of technology used. The estimated values of this metric are in Fig. 2. The results indicate multiple findings:

- All of the system EPBTs are estimated to be less than useful lifetime, which means that the PV systems are more sustainable and should be encouraged for their positive environmental benefits;
- The c-Si technology has greater values of energy contribution required and of energy output compared to the other PV technologies. However, the two effects are equal and have an EPBT almost identical to that of the p-Si and CIS technologies (only the CdTe has much smaller values);
- The results show that the EPBT varies greatly with the PV panel orientation and installation locations, and for the same type of solar cell used and modifying the installation location, it is possible to verify the following values:
  - In the case of the CdTe cells, the EPBT minimum and maximum values are 1.8 years and 2.1 years, with a variation of 0.3 years;
  - In the case of the CIS cells, the EPBT minimum and maximum values are 2.4 years and 2.8 years, with a variation of 0.4 years;
  - In the case of the p-Si cells, the EPBT minimum and maximum values are 2.5 years and 2.9 years, with a variation of 0.4 years;
  - In the case of the c-Si cells, the EPBT minimum and maximum values are 2.4 years and 2.8 years, with a variation of 0.4 years;
- Analysing the results within the same city, the results show that the minimum time required for the energy payback is always associated with the CdTe cell types. Modifying the types of cells for a given location is necessary to increase a certain amount of time:
  - Milan location, 0.7 years for the CIS and c-Si cells, 0.8 years for the p-Si cells;
  - Rome location, 0.5 years for the CIS cells, 0.7 years for p-Si cells, 0.6 years for the c-Si cells;
  - Palermo location, 0.6 years for the CIS and c-Si cells, 0.7 years for the p-Si cells;
- As can be expected, the shorter payback times are associated with the locations with a higher level of insolation. The best situation involves the use of the CdTe cells located in Palermo; the longer time for the energy payback is for a PV system with the p-Si cells in Milan.

According to the EPBT for the selected technologies cells, the indicator ranked from 1.8 to 2.9. The minimum value is related to the use of the CdTe cells for a plant located in Palermo, and the maximum is related to a p-Si PV system located in Milan. Significant research has already been performed to increase our understanding of the energy payback time of renewable investments. However, the present results indicate that the Italian EPBT is generally higher compared to the previous assessments of the alternative solar technologies. According to a recent work [9] (Table 4), the general EPBT for a CdTe system located in Europe is

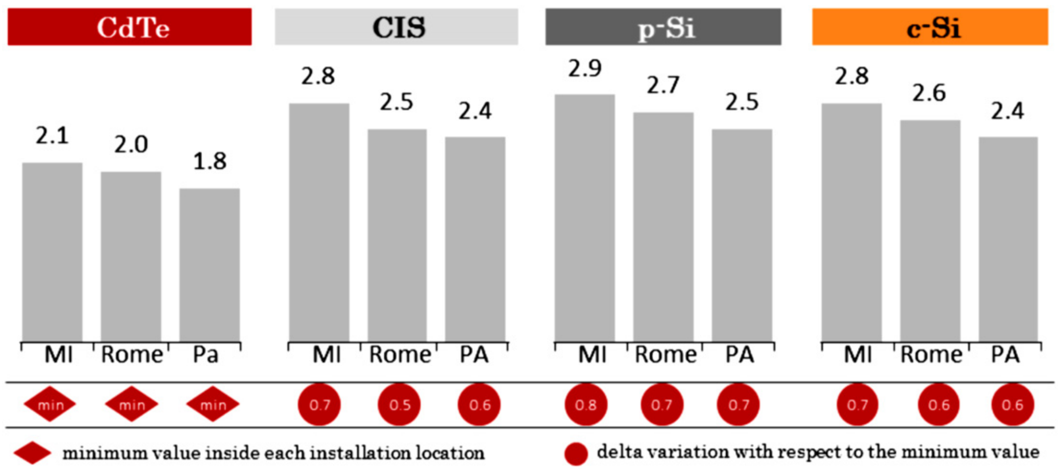

Fig. 2. EPBT for PV system located in Milan, Rome and Palermo (years).

1.0 year, although this result does not consider the entire life cycle of the energy production. In the present paper, the carbon dioxide and other gases emitted are also estimated for the extraction, processing, and disposal of the associated materials. For this reason, the minimum time required to recover the primary energy consumption is 1.8 for the system located in Palermo.

Moreover, the EPBT is strongly dependent upon the conversion factor of the annual power generation to primary energy. With respect to the average efficiency of the electricity generation projects in other countries (Table 7), the Italian conversion factor is greater, and this results in a greater EPBT.

6. Greenhouse gas per kilowatt hour

In this section, the attention is focused on the *Greenhouse Gas Emissions* and energy output of the PV system during its lifetime. These values are necessary to measure the GHG/kWh with respect to the installation location and the module type used

6.1. GHG_{EM} estimation

The GHG emissions normally occur during all of the phases of a life cycle of a PV system. Table 11 presents the GHG emissions pertaining to each non-renewable and renewable electricity generating sources for 1 kWp of monocrystalline cells [54].

During the first manufacturing step, installing the building-integrated PV system involves mounting the roofing panel, connecting the PV modules and installing and connecting the BOS. This step does generate CO_2 and other gases, and Kim and Fthenakis [54] estimate a 93.7% GHG emissions in this step. The GHG emissions during the plant operation are 3.5% of the total GHG.

The operational phase energy needs, such as those required for the operation of the energy metres [11], can be satisfied by what the PV system produces. This value should be reduced from that calculated in Eq. (3). Alternatively, the E_{OUT} value can be omitted and can withdraw from the national grid the energy required in this step. The GHG emissions related to the transport phase are, on average, 0.9% of the total gas emitted.

Included in the analysis is the energy embodied for decommissioning and the disposal steps. The decommissioning and disposal are generally considered negligible components of the energy input requirements and are frequently omitted from the analysis; while the future recycling programs are viable for some of the PV technologies, the amorphous silicon modules likely would be disposed of at the end of their useful life.

An extensive scientific literature review has been performed in this research. While normally not listed, the subdivided GHG emissions among the different steps, with respect to the global GHG values the literature values, are presented in Table 12. In the rest of the paper, the value of 2333 $KgCO_{2\text{-eq}}$ is used. This value is the most common in the analysed literature.

For the estimation of the GHG emissions from the other cell types, such as the E_{INPUT} variable, the values of Laleman et al. [35] are used (Table 13).

Table 11
GHG for a monocrystalline PV system.

		$KgCO_{2\text{-eq}}$/kWp	%	$KgCO_{2\text{-eq}}$
Manufacturing	GHG_M	2186	93.7	2186
Operations maintenance	GHG_{OM}	82	3.5	82
Transport	GHG_T	21	0.9	21
Disposal	GHG_D	44	1.9	44
Emitted	GHG_{EM}	2333	100	2333

Table 12
Review of GHG_{EM} for monocrystalline PV ($KgCO_{2\text{-eq}}$).

Reference	[35]	[54]	[3]
GHG_{EM}	1867	2333	3470

Table 13
GHG_{EM} for cells technologies ($kgCO_{2\text{-eq}}$).

Technology	c-Si	p-Si	CdTe	CIS
GHG_{EM}	2333	2199	2066	2133

6.2. $E_{OUT,GLB}$ estimation

The energy output of a PV system depends on several factors, such as the annual average insolation on an inclined PV module for different climatic zones, the sunshine hours per day, the solar radiation, and the temperature. The proper sizing and design of a PV system is essential for a reliable performance for a long period of time. Furthermore, there are electrical losses because of the inverter, transformer and connecting electrical resistance; for these reasons, with respect to the 1° annual E_{OUT} (Table 10), there is a 0.70% annual

reduction [46] (Table 14). The total value of the energy produced is determined by the sum of the annual values (Table 14).

6.3. GHG/kWh estimation and discussions

The greenhouse gas per kWh is estimated by the ratio between the values in Table 13 and Table 14.

From the gained results, the following can be emphasised (Fig. 3):

- All of the GHG/kWh values are less than those related to fossil fuels, and as a consequence, for the installation of all the PV system analysed, there is an environmental benefit;
- Analysing the results for a fixed type of cell technology, changing the city where the facility is located, the GHG/kWh values oscillate for the range:
  - 13 $gCO_{2\text{-eq}}$/kWh range for all PV technologies CdTe, CIS, p-Si or c-Si cells (the minimum and maximum values are respectively 79–92, 77–90, 72–85, 71–84);
- Inside the same location site, the minimum production of $gCO_{2\text{-eq}}$ is always linked to the c-Si type of cells. With respect to this minimum value, using the CdTe, CIS or p-Si cells, the GHG/kWh respectively increases
  - 8, 6 and 1 in Milan;
  - 7, 6 and 1 in Rome;
  - 8, 6 and 1 in Palermo.
- As can be expected, the lower levels of GHG/kWh are associated with locations with a higher level of insolation. The best situation is related to the use of the c-Si cells located in Palermo (71 $gCO_{2\text{-eq}}$); on the contrary, the greater GHG/kWh is related to a PV system based on the CdTe cells and located in Milan (92 $gCO_{2\text{-eq}}$). The two metrics of the EPBT and GHG strongly depend on the location of the PV system operation and the types of cells used, but are influenced differently by these factors.
- The crystalline cells are characterised by a higher level of electricity production compared to thin film technologies with a higher level of efficiency. For the thin film systems, in reference to the environmental performance regarding global warming, the environmental scores are slightly less than those of the crystalline technologies. Globally, the gas emission representing the numerator of the GHG metric is greater for the crystalline technologies with respect to the thin film type.

Table 14
$E_{OUT,GLB}$ for cells technologies located in Milan, Rome and Palermo(kWh).

	PV cells technology			
	CdTe	CIS	p-Si	c-Si
Milan	22,385	23,629	25,868	27,857
Rome	24,457	25,816	28,262	30,436
Palermo	26,270	27,730	30,357	32,692

The conducted detailed analysis on the GHG for the PV life cycle based on the four types of modules shows a minimum value of GHG emissions of 71 $gCO_{2\text{-eq}}$/kWh for the c-Si cells in Palermo and a maximum of 92 for the CdTe system located in Milan. These estimates are greater than the estimates presented in Table 2 for fossil fuel. However, the GHG indicators for the modules from the Italian plants are expected to decline compared to the previous literature results [11]. The CO_2 emissions of the average Italian electricity supply are greater than those of the average European supply because the gases emitted are estimated during the extraction, processing, and disposal phases.

In addition, to consider the rapid progress of the PV technologies, a decreased efficiency factor has been introduced.

7. Energy Return on Investment: estimation and results

For the estimation of the EROI, we need the inputs already estimated in previous sections: $E_{OUT,GLB}$ (Table 9) and E_{IN} (Table 14).

Our calculations of the EROI (Fig. 4) show that

- All of the EROI ratios are greater than 1, and as a consequence, for all of the PV system types, there is an environmental benefit;
- Analysing the results for a defined type of cell technology, changing the city where the facility is located, the EROI values oscillate within the range:
  - 1.5 for the PV based the CdTe cells (minimum 8.7–maximum 10.2);
  - 1.2 for the PV based on the CIS, p-Si or c-Si cells (the minimum and maximum values are respectively 6.7 and 7.9, 6.4 and 7.6, 6.7 and 7.9);
- At the same location, the maximum EROI is always linked at the CdTe type of cells. With respect to the maximum value, using the CIS, p-Si or c-Si cells, the EROI values respectively decrease
  - 2.0, 2.3 and 2.0 in Milan;
  - 2.1, 2.5 and 2.2 in Rome;
  - 2.3, 2.6 and 2.3 in Palermo.

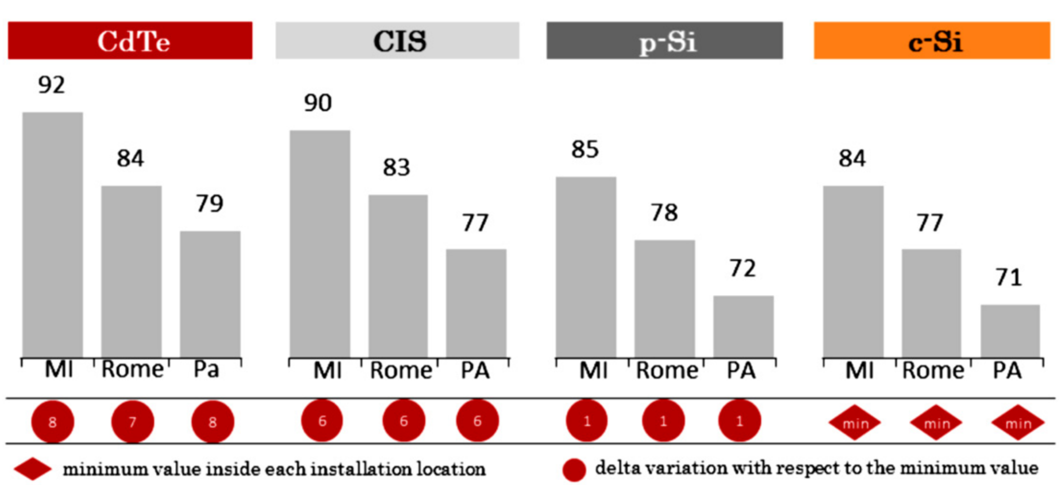

Fig. 3. GHG/kWh for PV systems located in Milan, Rome and Palermo ($gCO_{2\text{-eq}}$/kWh).

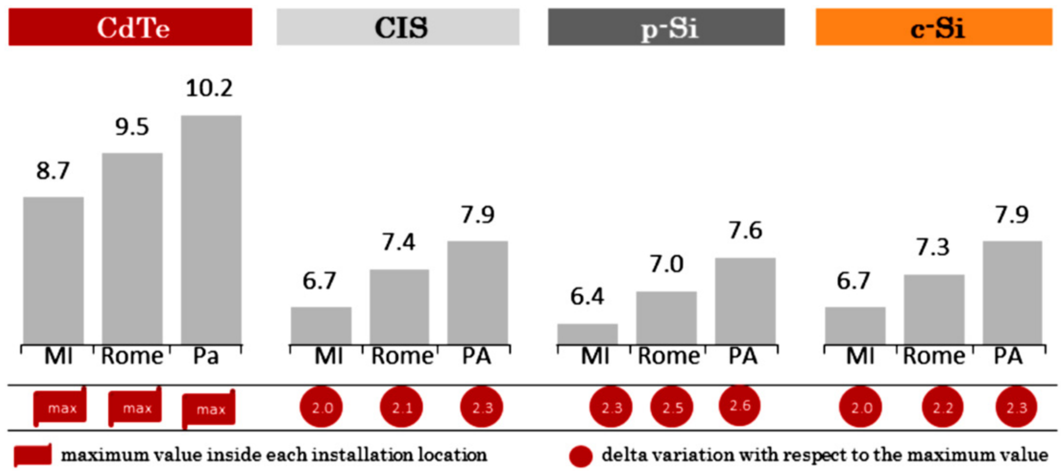

Fig. 4. EROI of PV systems located in Milan, Rome and Palermo.

– The higher levels of EROI are associated with the locations with a higher level of insolation. The worst situation is related to the use of p-Si cells located in Milan (6.4); the best one is related to a PV system based on the CdTe cells in Palermo. These results (in terms of the EROI) (Fig. 4) are consistent with those obtained in terms of the EPBT in Fig. 2.

The estimation of the EROI allows (unlike the EPBT) for the acknowledgement of the differences in technology lifetime. Using the EROI, this problem cannot be overcome, and according to the gained results, the EROI value for the different locations of production and types of cells are consistent with those of EPBT. The best solution is related to a CdTe cell system located in Palermo, both according to the EPBT and according to the EROI; the worst situation is related to the p-Si located in Milan.

8. Greenhouse Gas Payback Time: estimation and results

In an analogy to the energetic evaluation, the greenhouse gas payback time can be used to evaluate the time period after which the real environmental benefit starts. It can define the time period after which the real environmental benefit starts. The GHG_{EM} has been defined in Table 13, and the GHG_{SV} (Table 15) is given by the product of the E_{OUT} (Table 10) and the emission factor F_{MIXE}. The emission factor, based on the Italian electricity production mix, is equal to 0.531 kg of CO_2/kWh, [45] (the production of one kWh of electricity consumes the equivalent of 2.56 kWh of fossil fuels, emitting approximately 0.531 kg of CO_2).

Estimating the GPBT according to Eq. (9), the values of plants located in different cities and realised with different technologies are presented in Fig. 5. Multiple conclusions can be made as follows:

– All of the GPBT are estimated to be shorter than the system lifetime; thus, at the PV systems analysed, there are associated environmental benefits;
– With the crystalline cells, thin film can achieve a greater value of emissions “saved”. This result is also connected to the higher energy production;
– For a defined installation site, the GPBTs have the following range:
  - 0.4 years for PV based on the p-Si cells (minimum 2.6–maximum 3);
  - 0.5 kWh for PV based on the CdTe, CIS, or c-Si cells (the minimum and maximum values are respectively 2.8 and 3.3, 2.7 and 3.2, 2.5 and 3.0);

Table 15
GHG_{SV} for PV cells technology and installation location (kgCO2-eq/y).

	PV cells technology			
	CdTe	CIS	p-Si	c-Si
Milan	634	669	732	789
Rome	692	731	800	862
Palermo	744	785	859	925

– At the same location, the minimum GPBT is linked to both the p-Si and c-Si cells. With respect to the minimum value, using the CdTe or CIS cells, the GPBT increases in the same measure for Milan and Rome (respectively 0.3 or 0.2).
– The minimum GPBT is achieved in Palermo using the c-Si cells; the maximum value is for a CdTe PV located in Milan.

The GPBT of the PV systems analysed is estimated to vary from 2.5 to 3.3 years. If the PV system is installed in the same city, better results are always associated with the crystalline cells (both p-Si and c-Si, with a slight increase for p-Si in Palermo). According to this indicator, there is a clear distinction between the two technologies, with better performances in reference to the crystalline cells due to the ability of the present metric to quantify the main differences between the two groups. The modules based on the thin film and crystalline technologies exhibit their main differences in the sunlight-to-electricity conversion efficiency and power density. The crystalline modules require less space than thin-film modules for the same amount of power; thin film is less efficient in the conversion of sunlight to electricity. Because of this, with regard to the environmental performance for global warming, the thin film systems have environmental scores that are slightly lower than those of the crystalline technologies (Table 13). For all of these reasons, the crystalline systems allow us to reduce the years necessary for a PV system to balance the emission of greenhouse gases.

9. Greenhouse Gas Return on Investment: estimation and discussions

The levels of the $GHG_{SV,GLB}$ (defined in Table 16) and GHG_{EM} presented in Table 13 are necessary for the estimation of the GROI.

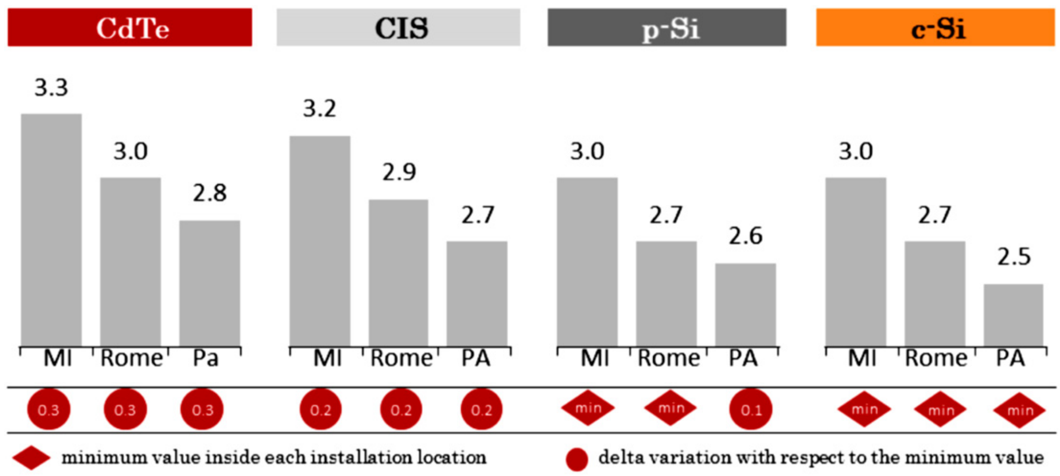

Fig. 5. GPBT of PV system located in Milan, Rome and Palermo (years).

Table 16
$GHG_{SV,GLB}$ for PV cells technology and installation location ($kgCO_{2-eq}$).

	PV cells technology			
	CdTe	CIS	p-Si	c-Si
Milan	11,864	12,523	13,710	14,764
Rome	12,962	13,682	14,979	16,131
Palermo	13,923	14,697	16,089	17,327

The results of the GROI analysis, using Eq. (11), are shown in Fig. 6 as follows:

- All of the GROIs assume a value greater than 1, and as a consequence, for the installation of all of the PV systems analysed, there is an environmental benefit;
- For a defined installation site, the GROIs have the following range:
  - 1 for the PV based on the CdTe and CIS cells (respectively minimum 5.7–maximum 6.7 and 5.9–6.9);
  - 1.1 for the PV based on the p-Si c-Si cells (the minimum and maximum values are respectively 6.2–7.3 6.3–7.4);
- At the same location, the maximum value of the GROI is always linked to the c-Si type of cells. With respect to the maximum value, using the CdTe, CIS or p-Si cells, the GROIs respectively decrease:
  - 0.6, 0.4 and 0.1 in Milan;
  - 0.6, 0.5 and 0.1 in Rome;
  - 0.7, 0.5 and 0.1 in Palermo.
- As can be expected, the higher levels of GROI are associated with locations with a higher level of insolation. The best situation is related to the use of the c-Si cells located in Palermo; the smallest GROI value is related to the PV system based on the CdTe cells and located in Milan. These results are consistent with those previously obtained.
- Using the same technology, cells and changing the location installation, the range is between 0.6 and 0.7.

The GROI metric results have been introduced as a compliment to the EROI, but unlike the EROI, the GROI accounts for the life cycle energy mix, for the efficiency, circularity, and supply chain of energy distribution, and for the energy offset by a new energy installation.

The estimation of the GROI allows (unlike the GPBT) for the acknowledgement of the differences in technology lifetime. Using the GROI, this problem cannot be overcome, and according to the gained results, the GROI value for the different locations of production and types of cells are consistent with those of GPBT. The best solution is related to a c-Si cell system located in Palermo, both according to the GPBT and according to the GROI; the worst situation is related to the CdTe located in Milan.

The installation location impacts the GROI through the same parameters, the first of which is a percentage change in the GHG/kWh results in a similar percentage change in the GROI. With respect to the insolation, a percentage change in insolation nearly results in the same percentage change in the GROI. In Fig. 7, the relationship between these two variables is presented; the more fit situation is related to the case of city change from Rome and Palermo. The insolation percentage variation is the same GROI metric increase if the system is p-Si-based.

The GROI allows for dynamic location-based decision making by inherently acknowledging that a choice to install a technology is a choice to not install or utilise an alternate technology.

The GROI encourages the quickest pathway to a reduction of greenhouse gas emissions globally by rewarding the replacement of high GHG/kWh technologies.

In this paper, a set of metrics has been analysed for the estimation of the energetic and environmental impacts of the PV systems for carbon abatement. There are clearly some interdependencies between the economic cost reduction and resource or environmental improvements. At least some of the cost reductions are related to the rapid developments in the performance of the technology, and the performance developments also have implications for the resource and environmental viability of PVs.

The PV systems cannot compete with conventional electricity sources on a unit cost basis but are viable in the sense that they provide significant environmental benefits. However, the PV systems significantly improve the viability of the technology in both economic and environmental terms. These systems have been analysed (for different technologies and locations) to be used to replace part of the power generated by the burning of fossil fuels and hence to reduce the impact of the greenhouse effect. The EPBT and GPBT allow for the analysis of whether a PV system is truly sustainable and green in nature. The general life of the PV systems is 20 years, and the EPBT and the GPBT estimated are far less than the lifetime of the PV systems. It may be concluded that the PV systems analysed are sustainable and green.

The GROI metric also has been introduced as a compliment to the EROI. The GROI specifically addresses the goal of alternative energy technology – climate change mitigation – while enabling

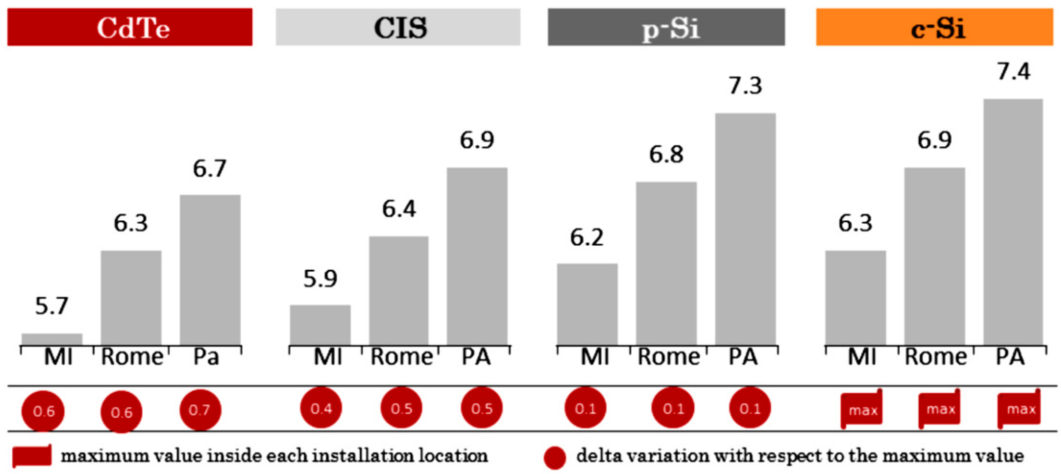

Fig. 6. GROI of PV systems located in Milan, Rome and Palermo).

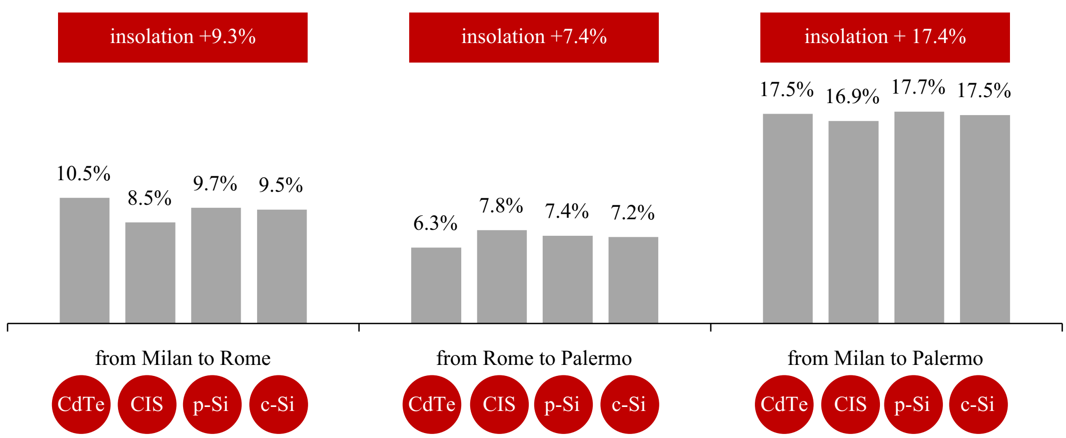

Fig. 7. Relationship between insolation level and GROI.

the quickest pathway to a reduction of greenhouse gas emissions globally by rewarding the replacement of high GHG/kWh technologies. The GROI estimates also indicate positive results towards the fastest route to climate change mitigation.

10. Conclusions

A life cycle assessment analysis considers the environmental burdens caused during the entire life cycle of a product production phase. It is a sustainable tool for analysing and assessing the environmental impacts that are caused through the production, use and disposal or recycling of a product system for specific applications.

In this article, more analyses are presented on the economic and environmental sustainability of a PV system. In the paper, four different types of PV systems are evaluated: CdTe, CIS, p-Si and c-Si. For each type of PV, to obtain general results, the environmental impact of a residential system is analysed in three regions with different locations – Milan, Rome and Palermo – and, as a consequence, different solar irradiation.

The role of energy used during the transport and disposal phases is typically neglected, but in the present paper, these contributions are quantified, as is the end-of-life phase; this consideration of multiple factors makes possible a complete comparison among different PV technologies.

The use of appropriate metrics for determining the goodness of a PV system is a critical phase of decision making. A PV system investment requires the use of potentially competing environmental indicators that have to be used to assess the environmental impact of a solar energy system. The EPBT and GPBT allow the analysis of whether a PV system is truly sustainable and green. The PV systems analysed are concluded to be sustainable and green.

The greenhouse gas metrics are considered here as relevant to the goal of mitigating climate change, and the energy metrics have been investigated as measures of efficiency. Additionally, the GHG return on investment metric is presented in the paper to address the drawbacks of the decision made solely using the EROI and GHG/kWh for new energy technologies. The estimated results of the EROI do not address the climate change concerns, which are the primary goal of alternative energy; the GHG/kWh metric only accounts for the insolation differences of alternative installation sites. The GROI accounts for the types of energy used during the technological life cycle, the efficiency, circularity, and supply chain of energy distribution, and the type of energy being offset at the point of use.

To assess the environmental impact of solar energy technology, several installation choices are investigated, and scenario analyses are defined in different locations.

The optimum energetic results are gained with thin film cells, whereas the best environmental results are achieved with crystalline cells.

The estimated metrics can be used by policymakers to establish incentives and is applicable to decision making beyond energy technology.

References

[1] Lloyd B, Forest AS. The transition to renewables: Can PV provide an answer to the peak oil and climate change challenges? Energy Policy 2010;38:7378–94.
[2] EPIA. Global market outlook for photovoltaic until 2015. 2011. p. 44.
[3] Cucchiella F, D'Adamo I. Feasibility Study of Developing Photovoltaic Power Projects in Italy: An Integrated Approach. Submitted for publication. 2011;12:1562–76.
[4] Eni. available at 〈http://www.eni.com/it_IT/home.html〉; 2011.
[5] Bhattacharya A, Kojima S. Power sector investment risk and renewable energy: A Japanese case study using portfolio risk optimization method. Energy Policy 2012;40:69–80.
[6] Koh SCL, Cucchiella F, Baldwin J, Shi G. Natural resource based green supply chain management. Supply Chain Management: An International Journal 2012;17:54–67.
[7] 〈http://investments2008.epia.org/〉.
[8] Azzopardi B, Mutale J. Life cycle analysis for future photovoltaic systems using hybrid solar cells. Renewable and Sustainable Energy Reviews 2010;14:1130–4.
[9] Fthenakis V, Alsema E. Photovoltaics energy payback times, greenhouse gas emissions and external costs. Progress in Photovoltaics: Research and Applications 2006;14:275–80.
[10] Xing Y, Hewitt N, Griffiths P. Zero carbon buildings refurbishment—A Hierarchical pathway. Renewable and Sustainable Energy Reviews 2011;15:3229–36.
[11] Fthenakis VM, Kim HC. Photovoltaics: Life-cycle analyses. Solar Energy. 2011;85:1609–28.
[12] Kim S, Dale B. Life Cycle Inventory Information of the United States Electricity System. The International Journal of Life Cycle Assessment 2004;10:294–304.
[13] Fthenakis VM, Kim HC. Greenhouse-gas emissions from solar electric- and nuclear power: A life-cycle study. Energy Policy 2007;35:2549–57.
[14] Fthenakis V, Kim HC. Energy use and greenhouse gas emissions in the life cycle of CdTe photovoltaics. MRS Proceedings. 2011;895.
[15] Fthenakis V, Alsema E. Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004-early 2005 status. Progress in Photovoltaics: Research and Applications 2006;14:275–80.
[16] Raugei M, Frankl P. Life cycle impacts and costs of photovoltaic systems: Current state of the art and future outlooks. Energy 2009;34:392–9.
[17] Leloux J, Narvarte L, Trebosc D. Review of the performance of residential PV systems in France. Renewable and Sustainable Energy Reviews 2012;16:1369–76.
[18] El Chaar L, Lamont LA, El Zein N. Review of photovoltaic technologies. Renewable and Sustainable Energy Reviews 2011;15:2165–75.
[19] Knier G. How do photovoltaics works? In: Science N, editor. 〈http://science.nasa.gov/〉: Nasa; 2002.
[20] Kalogirou SA. Solar Energy Engineering - Processes and Systems. Elsevier; 2009.
[21] Konarka. The Elevolution of photovoltaic technology. 〈http://www.konarka.com/2012〉.
[22] van Sark WGJHM, Brandsen GW, Fleuster M, Hekkert MP. Analysis of the silicon market: Will thin films profit? Energy Policy 2007;35:3121–5.
[23] EPIA. Solar generation 6 - Solar photovoltaic electricity empowering the world. 2011.
[24] Mekhilef S, Saidur R, Kamalisarvestani M. Effect of dust, humidity and air velocity on efficiency of photovoltaic cells. Renewable and Sustainable Energy Reviews 2012;16:2920–5.
[25] Agrawal B, Tiwari GN. Life cycle cost assessment of building integrated photovoltaic thermal (BIPVT) systems. Energy and Buildings 2010;42:1472–81.
[26] Ecoinvent. Report no. 6. available at 〈http://www.ecoinvent.ch/〉 2011.
[27] Meral ME, Dinçer F. A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems. Renewable and Sustainable Energy Reviews 2011;15:2176–84.
[28] Brecha RJ, Mitchell A, Hallinan K, Kissock K. Prioritizing investment in residential energy efficiency and renewable energy-A case study for the U.S. Midwest. Energy Policy 2011;39:2982–92.
[29] IEA. World Energy Outlook. 2011 EditionInternational Energy Agency; 2011.
[30] EPIA. Global market outlook for photovoltaic until 2014. 2010. p. 28.
[31] Hearps P, McConnell D. Renewable energy technology cost review. In: Institute ME, editor. Technical paper series: Melbourne Energy Institute; 2011.
[32] Chow TT. A review on photovoltaic/thermal hybrid solar technology. Applied Energy 2010;87:365–79.
[33] Bravi M, Parisi ML, Tiezzi E, Basosi R. Life cycle assessment of a micromorph photovoltaic system. Energy 2011;36:4297–306.
[34] Jiao Y, Salce A, Ben W, Jiang F, Ji X, Morey E, et al. Siemens and siemens-like processes for producing photovoltaics: Energy payback time and lifetime carbon emissions. JOM Journal of the Minerals, Metals and Materials Society 2011;63:28–31.
[35] Laleman R, Albrecht J, Dewulf J. Life Cycle Analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation. Renewable and Sustainable Energy Reviews 2011;15:267–81.
[36] Song JK, McGivern JV, Nichols KW, Markley JL, Sheets MD. Structural basis for RNA recognition by a type II poly(A)-binding protein. Proceedings of National Academy of Science USA 2008;105:15317–22.
[37] Hall C, Balogh S, Murphy D. What is the minimum EROI that a sustainable society must have? Energies 2009;2:25–47.
[38] Raugei M, Bargigli S, Ulgiati S. Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si. Energy 2007;32:1310–8.
[39] Stoppato A. Life cycle assessment of photovoltaic electricity generation. Energy 2008;33:224–32.
[40] Lu L, Yang HX. Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong. Applied Energy 2010;87:3625–31.
[41] De Wild-Scholten M. Energy payback times of PV modules and systems. V Workshop Photovoltaik-Modultechnik. Köln, 2009.
[42] Reich-Weiser C, Fletcher T, Dornfeld D, Horne S. Development of the Supply Chain Optimization and Planning for the Environment (SCOPE) Tool – submitted for puyblication 2008.
[43] Reich-Weiser C, Dornfeld D, Horne S. Greenhouse Gas Return on Investment: A New Metric for Energy Technology. 2008.
[44] ENEA. Rapporto Energia e Ambiente 2008: analisi e scenari; 2009.
[45] Ministero Ambiente. available at 〈http://www.minambiente.it/〉. 2010.
[46] Cucchiella F, D'Adamo I, Gastaldi M, Koh LSC. A photovoltaic system in a residential building: economic optimization and sensitivity analysis. 8th International Conference on Supply Chain Management and Information Systems. Hong Kong, 2010.
[47] Gurzenich D. Cumulative energy demand and cumulative emissions of photovoltaics production in Europe. Energy 2004;29:2297–303.
[48] Pacca S, Sivaraman D, Keoleian GA. Parameters affecting the life cycle performance of PV technologies and systems. Energy Policy 2007;35:3316–26.
[49] Tiwari A, Barnwal P, Sandhu GS, Sodha MS. Energy metrics analysis of hybrid - photovoltaic (PV) modules. Applied Energy 2009;86:2615–25.
[50] Governo italiano. Decreto legislativo 311; 2006.
[51] Nawaz I, Tiwari GN. Embodied energy analysis of photovoltaic (PV) system based on macro- and micro-level. Energy Policy 2006;34:3144–52.
[52] Radhi H. Energy analysis of façade-integrated photovoltaic systems applied to UAE commercial buildings. Solar Energy 2010;84:2009–21.
[53] Yang M, Blyth W. Modelling investment risks and uncertainties with real options approach. Paris: International Energy Agency Working Paper Series; 2007.
[54] Kim HC, Fthenakis VM. Life cycle energy demand and greenhouse gas emissions from an Amonix high concentrator photovoltaic system. IEEE Fourth World Conference on Photovoltaic Energy Conversion. Hawaii, 2006.